Spacecraft Motion Simulator and associated Modeling for Realistic Hardware-In-Loop Simulation

A.Somanathan
Control Dynamics and Simulation Group
ISRO Satellite Centre
Bangalore, INDIA
somanath@isac.gov.in

Srinivasarao. Lakkoju
Control Dynamics and Simulation Group
ISRO Satellite Centre
Bangalore, INDIA
slakkoju@isac.gov.in

Murali Krishna Bhagavan.G
Control Dynamics and Simulation Group
ISRO Satellite Centre
Bangalore, INDIA
bhagavan@isac.gov.in

P.Natarajan
Control Dynamics and Simulation Group
ISRO Satellite Centre
Bangalore, INDIA
pnrajan@isac.gov.in

***Abstract*—Hardware–In–loop simulation (HILS) is a realistic dynamic test environment for verification and validation of Attitude and Orbit Control System (AOCS) of a satellite. The tight attitude rate requirement of the order of +/- 5.0e-5 deg/sec of AOCS calls for high bandwidth high accuracy 3 degree of freedom spacecraft Angular Motion Simulator (AMS). The AMS along with dynamics model achieves the overall goal of assessing the performance of various control elements for all mission scenarios from satellite injection, transfer orbit acquisition, orbit raising, on-orbit, station-keeping & normal mode operations. The mechanism of AMS and associated modeling is successfully deployed in HILS testing of various satellite missions of Indian Space Program. This paper describes the closed loop system built around AMS for demonstrating the stringent pointing specification requirements of control system of a spacecraft.**

Keywords—Attitude and Orbit Control System (AOCS), Angular Motion Simulator (AMS), Dynamic Simulation Modeling (DSM), Hardware In-Loop Simulation (HILS), Spacecraft (S/C), On-Board Computer (OBC).

I. INTRODUCTION

The exclusive testing of satellite control system with all flight hardware components ensures reliable operation in space. The digital simulations using state of the art computers are used to validate control design with all non-linearity, noises, perturbations in control parameters and disturbance environment. But the participation of actual hardware and associated software is not present in case of digital simulation testing. The On-Board In-Loop Simulation (OILS) with actual flight software, with sensors & actuators modeling and without AMS verifies the functionalities of OBC.

Hardware In-Loop Simulation is an important mission critical activity which validates control algorithms of On-Board Computer (OBC) with all flight hardware in a dynamic simulation environment [1]. The flight sensors of satellite are mounted on AMS using suitable mechanical mounting fixtures. The spacecraft (S/C) instantaneous attitude information sensed by the sensors is processed by OBC. The required actuating control signal corresponding to attitude error and rate, generated by OBC, is fed to actuators. The closed loop action for sensors was achieved through table rotations as per the software commands of DSM corresponding to acquired actuator signal. This results in change in attitude of S/C which is sensed by sensors, thus closing the loop. A typical HILS block schematic is shown in Fig. 1.The computational requirement of simulation software for HILS of satellites includes the following:

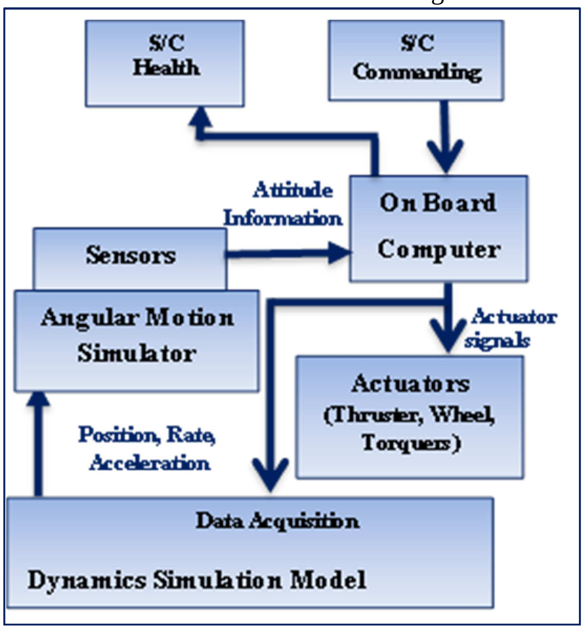

Fig. 1. Block Schematic of HILS

Proceedings of the 1st International and 16th National Conference on Machines and Mechanisms (iNaCoMM2013), IIT Roorkee, India, Dec 18-20 2013

1. Acquisition of control torque and health signals from flight control packages.
2. Computation of total torque acting on S/C. Simulation of kinematics & dynamics to generate S/C attitude and rate information.
3. Driving of AMS as per on-orbit attitude and rate data at every step size and address various scenarios for different kinds of missions.
4. Mission data processing for and display of S/C health information in engineering units.
5. Generation of S/C commands by mission control to all packages as per initialization, orbit sequence and termination of simulation.

This paper describes Angular Motion Simulator, its applications, mounting of sensors (Section II), the core & various computing models of DSM (Section III) for realistic simulation, AMS drive with instantaneous data (Section IV) and subsequent sections deals with test results (section V) and conclusions (section VI).

II. ANGULAR MOTION SIMULATOR

Angular Motion Simulator (AMS) is a 3 degree of freedom test platform for simulating attitude motion to flight sensors. The AMS as a unit consists of a simulator, a power cabinet and a control cabinet. A set of interconnecting cables are running between these units for signal transfer. Electrical slip ring of the simulator provides connections between Unit Under Test (UUT) and external test equipment and ensures the integrity of connections while the system undergoes mechanical motion. The three orthogonal gimbals of AMS namely inner, middle and outer are mapped to Yaw, Roll and Pitch axes of S/C. The electromechanical motion simulator is driven by independent synchronous motors for each axis [2]. The outer gimbal rotates about a vertical axis whereas the middle one rides on outer and rotates about horizontal axis. The inner gimbal fitted onto the middle, rotates about an axis orthogonal to middle axis. The design of an inner gimbal with its table top offers torsional rigidity and free floor space for convenient access to the UUT. Balancing is achieved for UUT by adding suitable counter weights to middle and inner gimbals for commencement of closed loop testing. The table provides very high rate stability and high accuracy better than 0.001% and very high bandwidth at the order of 35 Hz. It has temperature chamber to simulate extreme cold and hot temperature of the UUT. AMS is computer controlled system with the provision to change the plant model with inertial compensation provision, notch filtering to avoid interaction frequency from the payload along with lot of safety mechanism and safety limits.

A. *Applications of Angular Motion Simulator*

The AMS is being used for simulating S/C attitude motion by mounting a variety of sensors ranging from Inertial Reference Unit (IRU), Earth Sensor (ES), Digital Sun Sensor (DSS), Coarse Analog Sun Sensor (CASS), Four Pi Sun Sensor (FPSS), and Inertial Reference & Accelerometer Package (IRAP).

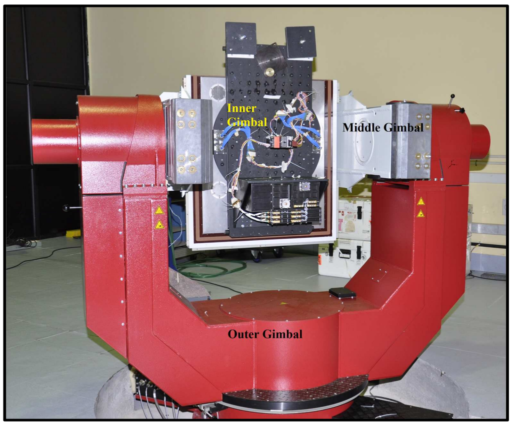

Fig. 2. Angular Motion Simulator

This configuration verifies the polarity of sensor axis w.r.t S/C axis, correctness of sensor and S/C axis mapping, sensor noise characteristics, sensor calibration and interfaces with on-board controller. The temperature chamber of AMS enables to test the control system performance with temperature sensitivity of flight sensors. This helps in S/C motion testing and visualization of on board scenario for demonstrating newly developed technologies and thus giving confidence in mission.

For S/C attitude control, three types of optical sensors are used namely ES for Earth pointing, Sun sensors for sun pointing and Star sensors for all 3-axes errors for any specific pointing. These optical sensors of the UUT are stimulated by stimuli generators such as earth simulator, sun simulator and star simulator. Various sensors are mounted on AMS as per required mechanical configuration. The ES is mounted with its optical center coinciding with the intersection point of all axes of AMS. Sun sensors are mounted either at the center or with a vertical displacement to accommodate ES. IRU is mounted with its axes coinciding with the gimbal axes. When all the sensors are mounted, the spatial distribution of the sensors results in a large offset of the heavy mass resulting in a flexible structure. The resultant oscillations in this configuration are avoided by augmenting strengthening members to mechanical mounting plate. After all the sensors are mounted, AMS will be balanced in the inner and middle axes over a wide range of positions. The safety of the flight sensors is ensured by safety settings in control unit of AMS.

III. DYNAMICS SIMULATION MODEL

DSM is a single closed loop simulation software package for all the control modes and all the sensor mounting configurations with a provision to select the required computing models through Graphical User Interface (GUI). It comprises of software modules for solar panel flexibility simulation, Earth rate & g-sensitive drift compensation, Wheel modeling, star simulation and various auxiliary modules.

A. *Core Computing Model*

The main function of the core module of DSM is to find new attitude information from acquired hardware control signals [3][4].

The governing equation is [11]:

$$T = \tau_c + \tau_d = I * \ddot{\theta} \qquad (1)$$

Where

T = Total torque in Nm;

τ_c= Control torque due to actuators in Nm

τ_d = Disturbance torque in Nm;

I = Satellite inertia in Kgm2;

$\ddot{\theta}$ = angular accelerationin rad/s2;

B. Solar Panel Flexibility Simulation

The S/C inertia is acted upon by control torques and disturbance torques which causes the S/C to undergo attitude motion in the form of attitude change and hence body rates.

Body rates are obtained by solving the following equation which incorporates all the necessary factors for rigid body and solar panels flexibilities [11].

$$\begin{bmatrix} \frac{I}{K} & \frac{K^T}{U} \end{bmatrix} \begin{bmatrix} \frac{\dot{W}}{\ddot{q}} \end{bmatrix} = \begin{bmatrix} \frac{T - W[IW + H_W]}{-2\gamma\dot{q}\sigma - \sigma^2 q} \end{bmatrix} \qquad (2)$$

Where,

I = Satellite Inertia Matrix in Kgm2 (3 x 3);

W = Body rate vector$\omega_x, \omega_y, \omega_z$in rad/sec (3 x 1);

T = Total torque vector in Nm (3 x 1);

Hw =Angular Momentum Vector due to Wheels in Nms (3 x 1);

K = Coupling matrix of two solar panels (10x 3);U = Unit Matrix (10 x 10);

γ = Damping vector of two solar panels (10 x 1);

σ= Frequency vector of two solar panels in rad/sec (1 x 10);

q = Angular motion of flexible modes of solar panel in rad/sec (10x1);

The body rate act on the coordinate transformation matrix to produce Euler rates and Euler angles [5] which are used to rotate the AMS gimbals outer(O), Middle(M), Inner (I).

$$\begin{bmatrix} \dot{\Psi} \\ \dot{\Phi} \\ \dot{\theta} \end{bmatrix} = A \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \qquad (3)$$

where,

$\Psi, \Phi, \theta =$ *Eulerangles in rad*;

$\dot{\Psi}, \dot{\Phi}, \dot{\theta} =$ *Eulerrates* in rad/sec;

$\omega_x, \omega_y, \omega_z =$ *Bodyrates in rad/sec*;

A = coordinate transformation matrix

$$= \begin{bmatrix} 1 & \frac{sin\Psi sin\Phi}{cos\Phi} & \frac{cos\Psi sin\Phi}{cos\Phi} \\ 0 & cos\Psi & -sin\Psi \\ 0 & \frac{sin\Psi}{cos\Phi} & \frac{cos\Psi}{cos\Phi} \end{bmatrix}$$

This coordinate transformation matrix is unique for a particular AMS gimbals axis definition. The above equation pertains to O-M-I gimbals mapped to S/C Pitch (P), Roll (R) and Yaw(Y) respectively.

C. Compensation for Earth rate and g-sensitive drift

IRU mounted on AMS is used in HILS testing to measure instantaneous rates of the S/C and is given as input to OBC. However, these measurements are affected by inherent drifts which result in slow divergence of actual measurements over time. These are subjected to misalignment and scale factor errors also. Hence IRU data used for attitude referencing by controller should have minimum effect of these errors. In HILS test environment, in addition to real attitude/rates, there are two main extraneous elements sensed by IRU namely Earth rate and g-sensitive drift. Even though, the global drift of IRU including fixed drift and other extraneous elements are compensated at and near AMS null position, large angle motions of the AMS during closed loop simulation result in erroneous IRU outputs. Hence these extraneous elements need to be compensated in real-time. This is performed in DSM by providing extra motions to the gimbals as computed from instantaneous AMS angles taking into account earth rate model, local g- model and g-sensitive drift coefficients. The governing equation is [6]:

$$\begin{bmatrix} \dot{Y} \\ \dot{R} \\ \dot{P} \end{bmatrix} = A * \left\{ \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} - \begin{bmatrix} \omega_{ex} \\ \omega_{ey} \\ \omega_{ez} \end{bmatrix} + SM^{-1} * G_s * \begin{bmatrix} -sinR \\ sinYcosR \\ cosYcosR - 1 \end{bmatrix} \right\} \qquad (4)$$

Where,

$\begin{bmatrix} \dot{Y} \\ \dot{R} \\ \dot{P} \end{bmatrix}$ = AMS rates in rad/sec;

Y, R, P are AMS angles in rad;

$A = \begin{bmatrix} 1 & \frac{sinYsinR}{cosR} & \frac{cosYsinR}{cosR} \\ 0 & cosY & -sinY \\ 0 & \frac{sinY}{cosR} & \frac{cosY}{cosR} \end{bmatrix}$=Transformation matrix;

$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$ = Body rates in rad/sec;

$\begin{bmatrix} \omega_{ex} \\ \omega_{ey} \\ \omega_{ez} \end{bmatrix}$ = Earth rate components as function of Y, R, and P in rad/sec;

$SM = \begin{bmatrix} SF_y & MY_r & MY_p \\ MR_y & SF_r & MR_p \\ MP_y & MP_r & SF_p \end{bmatrix}$ = IRU scale factor and misalignment matrix;

$G_s = \begin{bmatrix} G_{yy} & G_{yr} & G_{yp} \\ G_{ry} & G_{rr} & G_{rp} \\ G_{py} & G_{pr} & G_{pp} \end{bmatrix}$ = g-sensitive drift coefficients in rad/sec;

$\begin{bmatrix} -sinR \\ sinYcosR \\ cosYcosR - 1 \end{bmatrix}$= Resolution of local g-vector along gyro axes depending on axis definition;

D. Wheel Modeling

Wheel modeling [10] of DSM comprises of dynamic friction compensation and transformation from wheel to S/C body for angular momentum and torque computation. The AMS is driven by resultant control torque after compensating for estimated friction in real time.

1. Dynamic Friction Compensation for Wheels:

The wheel control torque generated by OBC based on attitude error is commanded to wheels for actuation. However, due to frictional losses in wheels, the desired speed is not achieved, which in turn leads to insufficient wheel torque generation. Frictional losses depend on wheel speed, stabilization time, temperature etc. which are time varying. DSM computes the losses due to friction using moving average concept with wheel Torque Control Signal (TCS) and wheel speed change, according to the following equation [11]:

$$\text{Friction} = \text{TCS}_{\text{avg}} - (I * d\omega/dt)$$

Where,

Friction= Wheel Friction in Nm;

TCS_{avg}=Average TCS in Nm;

I=Moment of inertia of wheel in Kgm2;

$\frac{d\omega}{dt} = (2 * \pi * \Delta V)/(60 * \Delta t)$ in rad/s2

ΔV = change of wheel speed in RPM (Revolutions Per Minute);

Δt is the sampling window time in sec;

2.Wheel angular momentum & torque computation:

Depending on the wheel mounting on S/C, the reaction torque and angular momentum generated during wheel actuation gets resolved along S/C axes. The transformation of momentum from wheel to S/C body axes for a typical tetrahedral wheel mounting along –ve Yaw axis is computed by [11]:

$$\begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} = \begin{bmatrix} -s(\beta) & -s(\beta) & -s(\beta) & -s(\beta) \\ s(\alpha)c(\beta) & c(\alpha)c(\beta) & -s(\alpha)c(\beta) & -c(\alpha)c(\beta) \\ c(\alpha)c(\beta) & -s(\alpha)c(\beta) & -c(\alpha)c(\beta) & s(\alpha)c(\beta) \end{bmatrix} \begin{bmatrix} H_{W1} \\ H_{W2} \\ H_{W3} \\ H_{W4} \end{bmatrix} \quad (5)$$

Where,

s (.) = sin (.); c(.) = cos(.);

H_X, H_Y, H_Z =Angular momentum in Nms along S/C Y, R, P axes respectively.

α =Angle in rad from Roll/Pitch axis to the projection of wheels on the R-P plane. β =Angle in rad between projection of wheel axis and R-P plane. H_{W1}, H_{W2}, H_{W3}, H_{W4}= Individual Wheel momentum in Nms.

Similar equations hold good for resolving the individual wheel torque to S/C axes.

E. Star Simulation

Star simulation of DSM for star sensor mounted in front of star simulator [8][9] verifies the sensor interface with OBC and helps in demonstrating the pointing requirement of AOCS. The instantaneous S/C attitude from sensors mounted on AMS, star catalog in Earth Centered Inertial (ECI) frame, star sensor mounting and orbit information is being used for generating star constellation on to star simulator.

F. Auxiliary computing models

The DSM incorporates software packages [3],[4] for control torque data acquisition & processing, thruster modeling comprises of thruster toque computation & thruster failure simulation, disturbance torque modeling consisting of slosh, liquid engine, gravity gradient and external disturbances, orbit simulation for satellite position and velocity computation [7], magnetometer simulation.

G. Graphical User Interface (GUI)

GUI configures a test case for creating on-board condition on ground. The S/C parameters like inertia, flexibility parameters, inclusion or exclusion of control and disturbance torques, angular momentum, sensor to AMS axes & polarity mapping, simulation time, initial error and rate simulation etc. are configurable elements of GUI. This also has provision to vary some of the parameters as a percentage of the nominal for simulating worst case conditions. This provides real time plotting of S/C parameters like attitude errors, rates, wheel speeds etc. for real time analysis during the simulation. Inputs used for simulation and the results of the simulation are stored in test case wise for future data analysis.

IV. ANUGLAR MOTION SIMULATOR DRIVE

The physical attitude motion of S/C under test is simulated by driving AMS with the closed loop demands as computed by DSM. The attitude, rate and acceleration information for each axis is posted to AMS in real-time at every integration step size through high speed fiber optic communication interface. This communication is a Virtual Memory Interface Connection (VMIC) which doesn't involve much of the host system time in data transmission to AMS.

V. TEST RESULTS

Fig.3. & Fig.4.shows a typical S/C sun acquisition control mode with positive pitch axis of the S/C pointing towards the sun. The IRU and sun sensor, stimulated by sun simulator are mounted on AMS as per configuration. The sun sensor gives Yaw, Roll attitude errors and IRU gives Pitch attitude error to OBC.

The test matrix of DSM includes the selection of thruster as actuator with required inertia, solar panels flexible simulation, test case run duration of 2400sec and close loop integration step size of 10 milliseconds. An initial error condition of S/C (Yaw= 30, Roll=30, Pitch= 10) degrees is created on AMS. The OBC actuates the thrusters corresponding to the attitude error sensed by sun sensor and IRU. The attitude convergence from initial condition (Fig.3) with required coasting rate (Fig.4) was demonstrated successfully using proposed mechanism of AMS and with associated DSM.

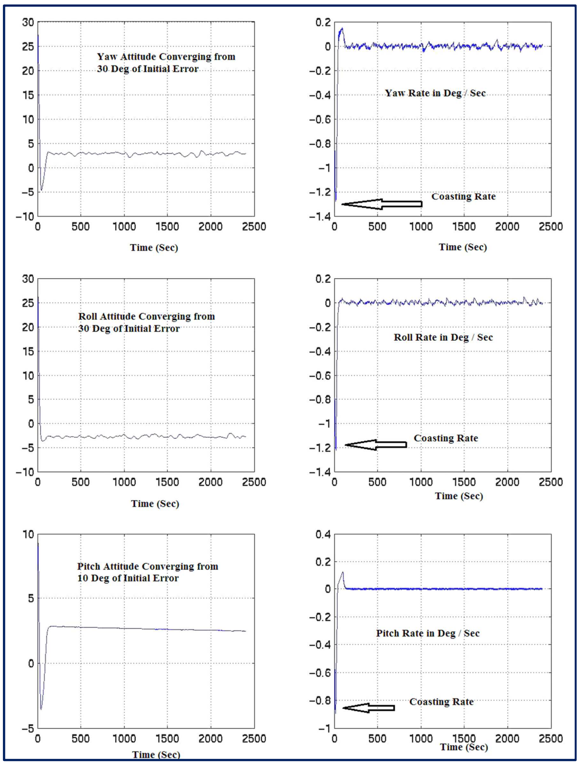

Fig.3 spacecraft Attitude Fig.4. spacecraft Rate

A typical HILS test reulst for a normal modepayload operation with IRU and star sensor in control loop is shown in Fig. 5.The pointing rate requirement of+/-5.0e-5 deg/sec alongS/C Y,R and P is demonstrated with proposed scheme.

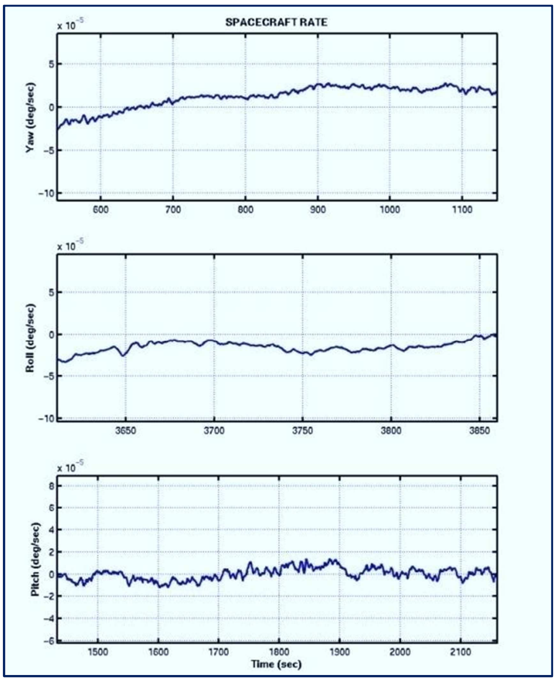

Fig.5. spacecraft Rate

VI. CONCLUSION

This paper brings dynamic simulation model for simulating the spacecraft conditions on ground and various applications of AMS and its role in conducting Hardware In-Loop simulation for S/C control system. During various control modes testing, deficiencies in the hardware, software and interfaces among subsystem of S/C have been brought out, analyzed and corrected to achieve flawless operation of AOCS in on-orbit. The mechanism of AMS and associated dynamic modeling is successfully used in closed loop testing of various satellite missions ranging from communication, remote sensing, navigational and recovery mission to recent deep-space mission of Mars Orbiter S/C control system evolution.

ACKNOWLEDGMENT

Authors wish to thank the entire team of HILS division for their cooperation, Control Dynamics and Analysis Divisions for their contributions. We would like to convey our gratitude to Mr. E Vasantha, Deputy Director, Controls & Digital Area for his encouragement.

REFERENCES

[1] Evolution of Hardware in Loop Simulation For Satellites at ISAC, ISRO-ISAC-TR-0852, Control Systems Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, July 2008.

[2] Instruction Manual IM-21143 for the Series AC3377.04-TCC Three Axis Position / Rate Table, ISRO-ISAC, Bangalore, July 2008.

[3] Software Document On Hardware-In-Loop Simulation For GEOSAT Satellites (INSAT 3B),ISRO-ISAC-INSAT-3B-PR-0169, Control Systems Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, August 2000.

[4] Software Document On Hardware-In-Loop Simulation for Indian remote Sensing Satellites(TES), ISRO-ISAC-TES-PR-0169, Control Systems Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, September 2003.

[5] James R.wertz, Spacecraft Attitude determination and Control, D.Reidel Publishing Company, Holland.

[6] G.MuraliKrishnaBhagavan,S.Ramaswamy,A.Somanathan,B.Kalpana " Earth-Rate and g-sensitive drift compensation for DTG in hardware-In-Loop-Simulation fo Space Missions", 2011 ISRO Conference on Computer Technology for Space, pp.110-115,published.

[7] Software Requirements Document for On-board Ephemeris and Orbit information generation S/W for SRE, ISRO-ISAC-SRE-PR-0437, Mission Development Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, January 2004.

[8] Major Modifications of HILS Facility for IRS-P6, ISRO-ISAC-IRS-P6-TE-0906, Control Systems Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, August 2003

[9] Modifications of HILS Facility for IRS-P5,ISRO-ISAC-IRS-P5-TE-1011, Control Systems Group, ISRO Satellite Centre, Indian Space Research Organization Bangalore, December 2004.

[10]A.Somanathan,GMKBhagvan,SurajPaul,AmitSingh,K.Parameswaran" Space Dynamics Modeling & Computation for Hardware-In-Loop Simulation of Indian Satellite", 2012 International Conference on Meta-Computing,published.

[11] Sidi, Marcel J, Spacecraft Dynamics and control: A Practical Engineering Approach Cambridge, 1997